

AS-TEXONO/03-08
February 7, 2008

Low Energy Neutrino Physics at the Kuo-Sheng Reactor Neutrino Laboratory in Taiwan

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A laboratory has been constructed by the TEXONO Collaboration at the Kuo-Sheng Reactor Power Plant in Taiwan to study low energy neutrino physics. The facilities of the laboratory are described. A limit on the neutrino magnetic moment of $\mu_{\bar{\nu}_e} < 1.3 \times 10^{-10} \mu_B$ at 90% confidence level has been achieved from measurements with a high-purity germanium detector. Other physics topics, as well as the various R&D program, are surveyed.

1. Introduction

The TEXONO¹ Collaboration² has been built up since 1997 to pursue an experimental program in Neutrino and Astroparticle Physics [1]. The “flagship” program is on reactor-based low energy neutrino physics at the Kuo-Sheng (KS) Power Plant in Taiwan. The KS experiment is the first large-scale particle physics experiment in Taiwan. The TEXONO Collaboration is the first research collaboration among scientists from Taiwan and China [2].

Results from recent neutrino experiments strongly favor neutrino oscillations which imply neutrino masses and mixings [3]. Their physical origin and experimental consequences are not fully understood. There are strong motivations for further experimental efforts to shed light on these fundamental questions by probing standard and anomalous neutrino properties and interactions [4]. The results can constrain theoretical models necessary to interpret the future precision data – or may yield surprises which have been the characteristics of the field. In addition, these studies could also explore new detection channels to provide new tools for future investigations.

2. Kuo-Sheng Neutrino Laboratory

The “Kuo-Sheng Neutrino Laboratory” is located at a distance of 28 m from the core #1 of the Kuo-Sheng Nuclear Power Station at the northern shore of Taiwan [1]. A multi-purpose “inner target” detector space of 100 cm×80 cm×75 cm is enclosed by 4 π passive shielding materials with a total weight of 50 tons. Different detectors can be placed in the inner space for the different scientific goals. The detectors are read out by a versatile electronics and data acquisition systems [5] based on 16-channel, 20 MHz, 8-bit Flash Analog-to-Digital-Convertor (FADC) modules. The readout allows full recording of all the relevant pulse shape and timing information for as long as several ms after the initial trigger. The reactor laboratory is connected via telephone line to the home-base laboratory, where remote access and monitoring are performed regularly. Data are stored and accessed with a cluster of multi-disks arrays each with 800 Gbyte of memory.

The measure-able nuclear and electron recoil spectra due to reactor $\bar{\nu}_e$ are depicted in Figure 1, showing the effects due to Standard Model [$\bar{\nu}_e e^-$ (SM)] and magnetic moment [$\bar{\nu}_e e^-$ (MM)] in $\bar{\nu}_e$ -electron scatterings [6], as well as in neutrino coherent scatterings on the nuclei ($\bar{\nu}_e N$ (SM) and $\bar{\nu}_e N$ (MM), respectively). The uncertainties in the low energy part of the reactor neutrino spectra require that experiments to measure $\sigma[\bar{\nu}_e e^-$ (SM)] should focus on higher electron recoil energies

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($T > 1.5$ MeV), while MM searches should base on measurements with $T < 100$ keV [7]. Observation of $\bar{\nu}_e N(\text{SM})$ would require detectors with sub-keV sensitivities.

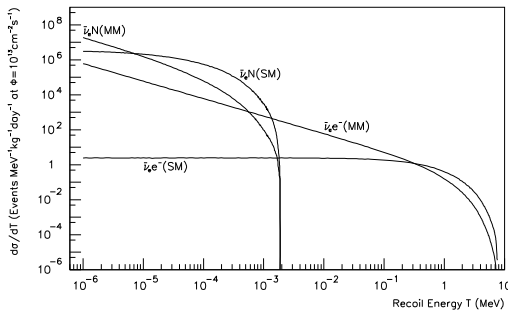


Figure 1. Differential cross section showing the recoil energy spectrum in $\bar{\nu}_e$ -e and coherent $\bar{\nu}_e$ -N scatterings, at a reactor neutrino flux of $10^{13} \text{ cm}^{-2} \text{ s}^{-1}$, for the Standard Model (SM) processes and due to a neutrino magnetic moment (MM) of $10^{-10} \mu_B$.

Accordingly, data taking were optimized with these strategies. An ultra low-background high purity germanium (ULB-HPGe) detector was used for Period I (June 2001 till May 2002) data taking, while 186 kg of CsI(Tl) crystal scintillators were added in for Period II (Jan 2003 till Sept 2003). Both detector systems operate in parallel with the same data acquisition system but independent triggers.

3. Neutrino Magnetic Moment Searches with Germanium Detector

The ULB-HPGe is surrounded by NaI(Tl) and CsI(Tl) crystal scintillators as anti-Compton detectors, and the whole set-up is further enclosed by another 3.5 cm of OFHC copper blocks, and housed in a radon shield. After suppression of cosmic-induced background, anti-Compton vetos and convoluted events by pulse shape discrimination, a background level at 20 keV at the range of $1 \text{ keV}^{-1} \text{ kg}^{-1} \text{ day}^{-1}$ and a detector threshold of 5 keV are achieved. These are the levels comparable to underground Dark Matter experiment. Comparison of the mea-

sured spectra for 4712/1250 hours of Reactor ON/OFF data in Period I [8] shows no excess and limits of the neutrino magnetic moment $\mu_{\bar{\nu}_e} < 1.3(1.0) \times 10^{-10} \mu_B$ at 90(68)% confidence level (CL) were derived.

Depicted in Figure 2a is the summary of the results in $\mu_{\bar{\nu}_e}$ searches versus the achieved threshold in reactor experiments. The dotted lines denote the $R = \sigma(\mu)/\sigma(\text{SM})$ ratio at a particular $(T, \mu_{\bar{\nu}_e})$. The KS(Ge) experiment has a much lower physics threshold of 12 keV compared to the other measurements. The large R-values imply that the KS results are robust against the uncertainties in the SM cross-sections. The neutrino-photon couplings probed by μ_{ν} -searches in ν -e scatterings are related to the neutrino radiative decays (Γ_{ν}) [9]. Indirect bounds on Γ_{ν} can be inferred and are displayed in Figure 2b for the simplified scenario where a single channel dominates the transition. It corresponds to $\tau_{\nu} m_{\nu}^3 > 2.8(4.8) \times 10^{18} \text{ eV}^3 \text{ s}$ at 90(68)% CL in the non-degenerate case. It can be seen that ν -e scatterings give much more stringent bounds than the direct approaches.

4. Other Research Subjects

The KS data with ULB-HPGe are the lowest threshold data so far for reactor neutrino experiments, and therefore allow the studies of several new and more speculative topics. Nuclear fission at reactor cores also produce electron neutrino (ν_e) through the production of unstable isotopes, such as ^{51}Cr and ^{55}Fe , via neutron capture. The subsequent decays of these isotopes by electron capture would produce mono-energetic ν_e . A realistic neutron transfer simulation has been carried out to estimate the flux. Physics analysis on the μ_{ν} and Γ_{ν} of ν_e will be performed, while the potentials for other physics applications will be studied. In addition, potentials for an *inclusive* analysis of the anomalous neutrino interactions with matter, as well as studies on neutrino-induced nuclear transitions will be pursued.

Period II data taking includes an addition of an array of 186 kg of CsI(Tl) crystals. [10], each module being 2 kg in mass and 40 cm in length. The physics goal is to measure the Standard Model neutrino-electron scattering cross sections, and thereby to provide a measurement of $\sin^2 \theta_W$ at

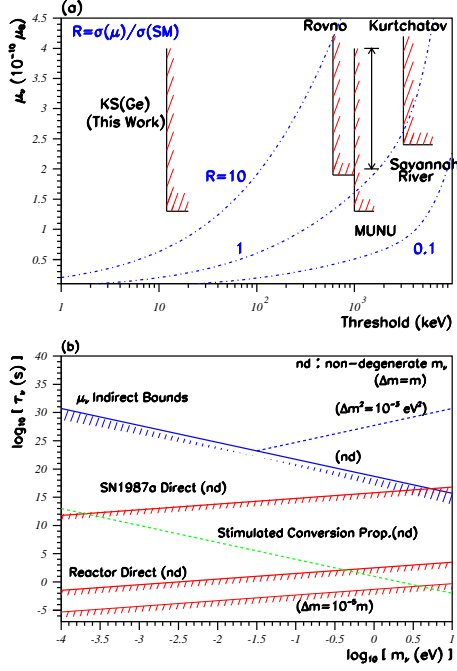


Figure 2. Summary of the KS Period-I results in (a) the searches of neutrino magnetic moments with reactor neutrinos, and (b) the bounds of neutrino radiative decay lifetime.

the untested MeV range. The strategy [7] is to focus on data at high (>2 MeV) recoil energy where the uncertainties due to the reactor neutrino spectra are small. The large target mass compensates the drop in the cross-sections at high energy.

In addition, various R&D projects [1] are pursued in parallel to the KS reactor neutrino experiment. In particular, a prototype ultra-low-energy germanium (ULE-HPGe) detector of 5 g mass is being studied, with potential applications on Dark Matter searches and neutrino-nuclei coherent scatterings. A hardware energy threshold of better than 100 eV has been achieved, as illustrated in Figure 3. The ULE-HPGe is placed inside the shieldings at the KS laboratory where the goal will be to perform the first-ever background studies at the sub-keV energy range. It is technically feasible to build an array of such detectors to increase the target size to the 1 kg mass range.

The TEXONO research program is supported by the National Science Council, Taiwan and the

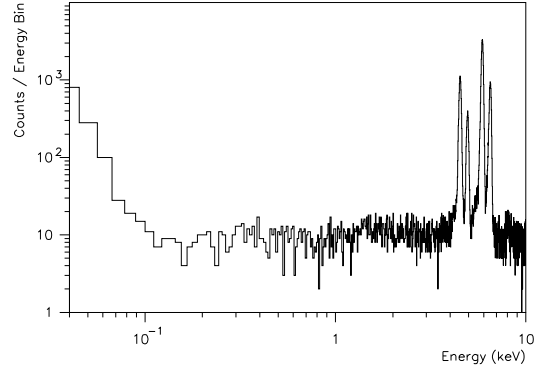


Figure 3. Energy spectrum with the ULE-HPGe, indicating a detector threshold lower than 100 eV. The peaks are from an ^{55}Fe source and from back-scattering with Ti.

National Science Foundation, China, as well as by the operational funds from the collaborating institutes.

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